The Production and Properties of Soft Röntgen Radiation.

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(Communicated by Sir J. J. Thomson, F.R.S. Received January 20,—Read February 16, 1911.)

There is a class of problem of the greatest interest in connection with primary Röntgen rays, which as yet has received but little attention from experimental investigators. The kind of problem referred to is indicated by the following two leading questions :—

(1) How do the properties of Röntgen radiation depend on the velocity of the parent cathode rays ?

(2) How do the properties of Röntgen radiation depend on the nature of the anticathode used to arrest the motion of the parent cathode rays ?

The present communication has to do with soft Röntgen radiation such as is produced in a discharge tube working at only a few thousand volts. The only investigator who appears to have worked with such rays is W. Seitz, and his experiments are referred to later. As a preliminary it will be convenient to present a general view of the ground which will be covered, and to indicate broadly the method employed.

In the present experiments slow cathode rays of known velocity were directed on to one of a series of metallic anticathodes, the Röntgen rays so produced being led out into the open air through an aluminium window, and there tested. The tests applied to the rays were quantitative measurements of :—

(1) Their energy, as indicated by the ionisation produced in a definite thickness of air; (2) their penetrating powers, as indicated by the values of their absorption coefficients in different materials; and qualitative observations on (3) their power of producing corpuscular emission when incident on metal surfaces.

These three properties of Röntgen rays were chosen as being the most important, and the most easily observed. The first two are especially important, since a pulse radiation is sufficiently defined for some purposes by a knowledge of its energy and absorption coefficients. A preliminary account of the work was given in August of last year to the Cambridge Philosophical Society.*

* Whiddington, 'Proc. Camb. Phil. Soc.,' vol. 15, Part VI, p. 574.

This paper is divided into the following sections:—

§ 1. A description of the apparatus.

§ 2. A theory of the influence of the aluminium window on the constitution of the emerging Röntgen radiation.

§ 3. The dependence of the *energy* of Röntgen radiation—

(*a*) On the nature of the anticathode.
(*b*) On the velocity of the parent cathode rays.

§ 4. The dependence of the *absorption coefficients* of Röntgen radiation—

(*a*) On the nature of the anticathode.
(*b*) On the velocity of the parent cathode rays.

§ 5. The *corpuscular radiation* excited by the incidence of Röntgen radiation on metallic surfaces.

§ 6. Summary and conclusions.

§ 2 occupies the place it does because the theory there advanced makes it much easier to remember the somewhat complicated and otherwise disconnected results of §§ 3 and 4.

§ 1. The Apparatus.

The apparatus can be described conveniently under two main headings: (1) That part of it which generated the radiation, *i.e.* the discharge tube; (2) That part which tested the rays, *i.e.* the ionisation chamber and its connections.

(1) *The Discharge Tube.* (Fig. 1.)—The discharge tube consisted of a tube 65 cm. long and 4 cm. in diameter (its length being at right angles to the

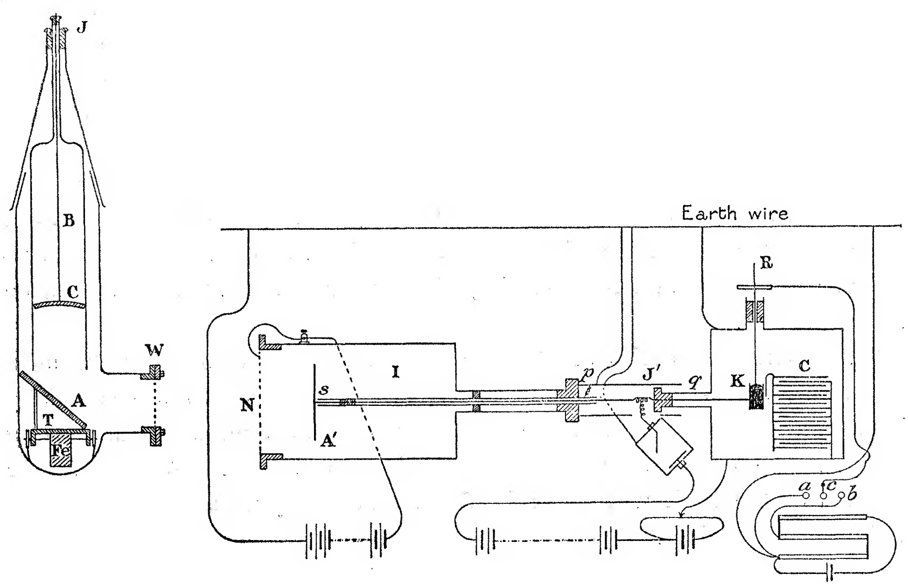

Fig. 1.

plane of the figure), along the bottom of which aluminium rails were laid down. This tube was fused to two slightly narrower and much shorter side tubes in the manner indicated in the figure. The horizontal one was 5 cm long, terminating with a thin aluminium window; the vertical one was about 30 cm. long, ending in a ground-glass joint. The plane containing these two tubes was at right angles to the length of the long tube. An aluminium carriage T ran on wheels along the track already referred to. This carriage carried a row of anticathodes of various materials, all inclined at about 45° to the horizontal. The materials used were Ag, Al, Sb, Cu, Fe, Ni, Pb, Pt, Sn, Zn. Their surfaces were ground smooth and finally polished with jeweller's rouge. The carriage T was magnetically controlled from outside by means of an electro-magnet and a bar of soft iron mounted under the carriage. The upper flange of the ground-glass joint J carried a tube B, enclosing a concave cathode C mounted at a convenient distance from the carriage. The joints at J were made tight with sealing wax.

The tube B, which fitted very tightly round the cathode C, served two purposes: firstly, it prevented the cathode from sputtering on the walls of the outer tube, and secondly, it helped to concentrate the cathode stream down the centre of the tube. It was found to be extremely important for quantitative work to prevent sputtering on the outer tube, since when it becomes conducting the beam of cathode rays is irregularly attracted to the walls owing to spasmodic induction effects.

The parallel beam of cathode rays striking an anticathode A produce Röntgen rays,* some of which pass down the horizontal tube and emerge through the window W.

The window consisted of a thin sheet of aluminium foil (0·002 cm. thick) supported on a coarse brass-wire grid. The grid was mounted on a heavy brass flange which was waxed on to the end of the horizontal tube. A brass annulus could be screwed down tightly on this flange, thus gripping the foil and making all air-tight. The tube was in direct communication with a Töpler mercury pump and a charcoal liquid-air tube.

In all experiments the anticathode system, consisting of rails and carriage, was connected to earth and made the anode. The window could either be earthed or charged to a potential, as occasion required. The experiments described below were carried out with potentials between the cathode and anode of the tube† up to 3600 volts. The potential up to this point was

* If the potential generating the cathode rays is say 2000 volts, and the anticathode is Pb, then the emerging radiation will for convenience be termed the 2000 volt radiation from Pb.

† Hereafter referred to as "the generating potential."

obtained from a battery of small accumulators. The high potential was connected to the tube in series with a high voltage key, a milliampère meter and a variable liquid rheostat (copper sulphate in water). The milliampère meter was a Weston instrument, each division being equivalent to 1/10 milliampère. The variable liquid rheostat was operated from a distance by a cord passing over pulleys, and gave a control of about 200 volts on the tube. The potential across the tube (*i.e.* between the anode and the cathode) was measured by a Braun electrometer, with a scale which could be read to 20 volts between 500 and 3500 volts.

Now it is well known that the cathode rays produced by a steady discharge from cells are homogeneous as regards their velocity, which is approximately given by the relation

$$2e/m \,.\, \mathrm{V} = v^2,$$

where

e/m = the universal charge to mass ratio (E.M. units),

v = the velocity of the cathode rays,

V = the potential in E.M. units applied to the terminals of the tube, *i.e.* the reading of the voltmeter $\times 10^8$.

Thus the reading of the voltmeter, multiplied by $2e/m \times 10^8$, gives approximately the square of the velocity of the cathode rays within the tube.

The vacuum in the tube was initially adjusted by use of the Töpler to give a current of 0·2 milliampère at approximately the required potential, the final adjustment being made with the liquid resistance. During the course of a long run the potential across the tube would gradually fall, indicated rather by a diminution in the intensity of the emergent Röntgen rays than by the reading of the electrometer. This was due to the liberation of electrode-gas, which could be absorbed by turning on the charcoal-tube tap for a few moments. After a few months' use, however, this effect became extremely small.

(2) *The Ionisation Chamber and its Connections.*—The ionisation chamber I (fig. 1) was a cylinder of brass, fitted with a detachable gauze front N. Both the gauze and the case of the chamber were usually charged to a saturating potential. To obviate the leakage of charge from the case to the insulated electrode A′, the wire support was encased in and insulated from a brass sheath tube S kept permanently connected to earth. This arrangement somewhat increased the electric capacity of the measuring system, but not to any serious amount. This sheath tube had the additional and very great advantage of completely protecting the insulation which really mattered,

and this insulation once put in and enclosed in this way remained good almost indefinitely.

The electrode A′ was connected to a mercury key K, enclosed in an earthed box containing a capacity C which could be added to the insulated system in connection with the gold leaf and thus diminish the sensibility. It was necessary in some experiments to adjust rapidly the distance of the gauze N from the window W. For this reason the whole measuring system—chamber, key, and electroscope—were mounted together on a rigid movable platform. It was then easy to move the whole system relative to the X-ray tube. Ebonite insulation was used throughout, and except in very damp weather proved very satisfactory. The absorbing screens had of necessity to be extremely thin, on account of the very low penetrating power of the rays dealt with. The thinnest obtainable leaf was used. The thicknesses were obtained by weighing. The screens were mounted on metal frames fixed to a geometrical slide, the whole being earthed. The geometrical slide enabled any required screen to be inserted with a minimum of delay. This time-saving device was found to be necessary, since it was not often that the tube would run steadily for long at a time.

§ 2. A Theory of the Influence of the Aluminium Window on the Constitution of the Emerging Röntgen Rays.

The experiments described in §§ 3 and 4 are so diverse in their nature and apparently so disconnected that it seems advisable to precede the experimental results by a theory which welds them together, and so aids the memory. This is the only excuse for presenting the following theory here instead of later, and it is to be regarded as tentative, since its simplicity must needs suffer should factors like selective transmission and so on be taken into consideration.

It is well known that many metals can be made to give out characteristic secondary radiation when stimulated by a suitable primary beam. The distinguishing feature of a characteristic radiation, according to Barkla, is its individuality. The quantity may depend on circumstances, but never the quality. It is, however, only when the primary beam contains a constituent more penetrating than the characteristic to be excited that the stimulation can be effected. This law governing the emission of characteristic radiations, in fact, is closely analogous to that law found by Stokes to be true in cases of light fluorescence. The recent researches of Prof. R. W. Wood, however, have shown that there are cases of light fluorescence in which Stokes's law is flagrantly disobeyed.

The possibility of similar exceptions to the parallel law of characteristic radiation or Röntgen ray fluorescence is indicated by the easy explanation on such an hypothesis of the otherwise hardly explicable results in connection with aluminium described in this paper. The basal assumption is this, that aluminium is capable of emitting a characteristic radiation which may be more penetrating than the exciting primary. Put in other words, it is assumed that Al is an exception to Stokes's law as applied to Röntgen ray fluorescence.

We will now consider what, on such an hypothesis, will be the state of affairs on the emergent side of a plate of aluminium (such as the window of the discharge tube) on which a beam of Röntgen rays is incident.

If the rays are excessively soft, their intensity on the emergent side will be very small—let us suppose inappreciable. Now imagine the incident primary beam to become gradually more penetrating while keeping its energy constant. Then, if the Al emit no secondary rays, there will come a stage (α), corresponding to a penetrating power P_C of the primary rays, when the emergent radiation becomes just strong enough to be detected. But it is conceivable that if the Al were to emit a secondary radiation of greater penetrating power than P_C, radiation might escape from the emergent side of the plate even if the incident primary rays possessed a penetrating power less than P_C.

This would happen if $P_{AL} > P_C$, where P_{AL} is the penetrating power of the characteristic Al radiation, P_C is the penetrating power corresponding to that quality of incident beam, which, in the absence of secondary effects, would just emerge in measurable quantity. The condition $P_{AL} > P_C$ involves the violation of the "Röntgen ray fluorescence" law referred to above.

In the apparatus shown in fig. 1 it will be seen that the Röntgen radiation produced by the incidence of the cathode stream on the target A must pass through the Al window W before reaching the testing vessel I.

The above considerations show that it is not impossible, with certain assumptions, for radiation to be detected by the vessel I even if the primary radiation from A is too absorbable to penetrate the window. As a sort of corollary it would follow that up to a certain limit of generating potential the quality of the emerging radiation would be constant; that is, the penetrating power of the emergent Röntgen radiation would remain apparently constant and independent of the velocity of the cathode rays striking the target (see fig. 7).

It is now necessary to consider some other and more complicated consequences of a violation of the "fluorescence law." There will be no further assumptions made, but it will be necessary to anticipate some of the simpler experimental results of §§ 3 and 4.

(1) The materials experimented with can be assigned positions in one of two classes according to their power or inability of emitting secondary Röntgen radiations. Group A, which includes Al, contains those anticathodes which emit secondary radiations, while Group B—the larger class—contains those which do not. This is a purely experimental classification.

Metals of Group A when subjected to a beam of cathode rays, and so to a beam of primary Röntgen rays, are imagined to be capable of emitting characteristic radiations of the type conceived above; whereas metals falling into Group B are supposed to emit no secondary radiation when placed under similar conditions.

(2) Experimental analysis of the radiations from members of Group B shows that they are all of the same quality at the same generating potential, but that their penetrating powers increase with the generating potential.

So much for the experimental results which it is necessary to anticipate for the purposes of the following considerations. Consider, first, the constitution of the radiation from a representative anticathode of Group B. Since the rays have to pass through the Al window they must contain a certain amount of the Al characteristic radiation. If the generating potential is low enough, the radiation will consist wholly of this Al characteristic. But with increasing generating potential the primary rays from the anticathode will become hard enough [stage (α)] to penetrate the window and so form a constituent of the emergent radiation. Further increase of the generating potential will have no influence on the quality of the secondary radiation from the window, but it will have the effect of increasing the penetrating power of the primary radiation from the anticathode. A stage will be reached when this primary radiation will possess a penetrating power greater than that from the window. A representative member of Group A can be regarded as emitting a radiation which is the same as that from a typical member of Group B with the addition of a strong secondary radiation from the anticathode itself. This strong secondary radiation can be regarded as the partial return in the direction of observation of the forward directed hemisphere of radiation spreading down into the anticathode. In the case of anticathodes of Group B it is supposed that this forward hemisphere is absorbed and lost in the anticathode, although of course it may be partially scattered.

Fig. 2 will now be readily understood. It is intended to represent in a quantitative sort of way possible analyses of the radiations from members of Groups A and B at two different cathode ray velocities corresponding to generating potentials V and V_1. The figure, for simplicity, takes Al as typical of Group A. PQ represents, in section, the plane of the window

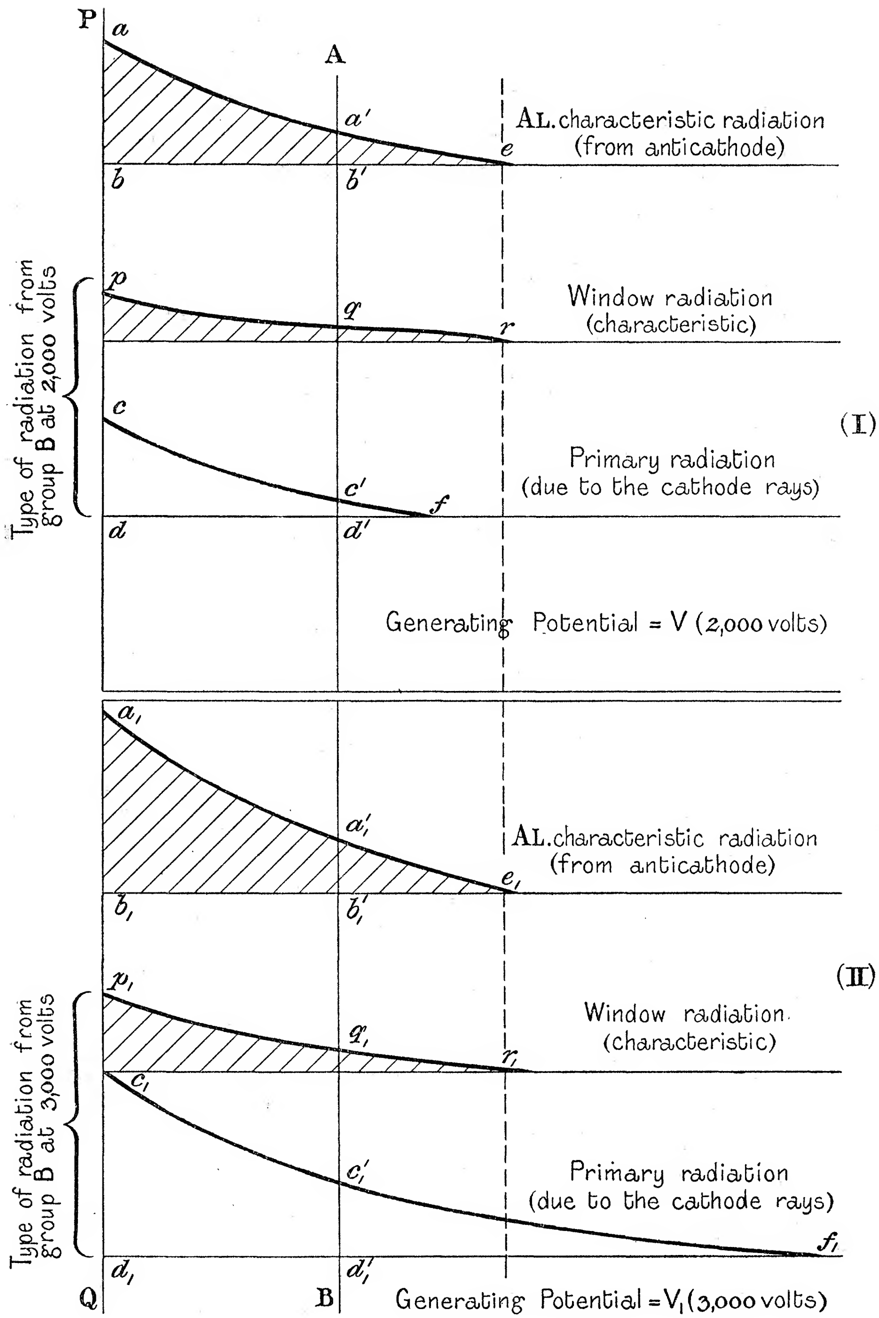

Fig. 2.

distances measured at right angles to PQ representing actual distances at right angles from the window. Take the top curve *aa′e*, which represents

the characteristic radiation from an Al anticathode at V volts. The radiation represented by this curve can penetrate no further than the distance *be*, or, rather, beyond *e* it produces no measurable ionisation. Further, the area included between *aa'e* and *be* represents the energy of the emerging radiation as measured by the ionisation produced on its total absorption. If, however, only the radiation to the right of *a'b'* be absorbed, then the observed energy (ionisation) will be given by the area included between *a'e* and *b'e*.

These explanatory remarks apply equally to the other five curves. It may be here pointed out that of the six curves in fig. 2, four possess the same penetrating power, and, in fact, are representatives of the same type of radiation produced under different circumstances. These four curves are shaded in the diagram.

In fig. 2, $V < V_1$, indicating that the variable primary constitutent *cc'f* is less penetrating at V volts than the corresponding constituent $c_1c_1'f_1$ at V_1 volts. Consider (i) of fig. 2 first of all. The two bracketed curves *pqr* and *cc'f* represent the constitution of the radiation from some member of Group B. The invariable window radiation is represented by *pqr*, while the primary component (at this potential supposed to be softer) is represented by *cc'f*.

The total ionisation produced by this radiation

$$= [\text{area } pqr + \text{area } cc'f].$$

The total ionisation which would be produced by any other member of Group B would be

$$= s\,[\text{area } pqr + \text{area } cc'f],$$

where *s* is the appropriate constant.*

Now the constitution of the radiation from an Al anticathode can be represented by the three curves *aa'e*, *pqr*, and *cc'f*, the latter two curves requiring a suitable factor when their areas are taken into account. The curve *aa'e* represents the secondary characteristic radiation spreading out from the anticathode.

The total ionisation produced by this radiation

$$= \text{area } aa'e + \alpha\,[\text{area } pqr + \text{area } cc'f].$$

The area *aa'e* is here much the more important, since α is a factor much less than unity. This factor is introduced because, apart from the secondary radiation represented by the area *aa'e*, the Al radiation is the same as that from members of Group B, only on a smaller scale.

* This involves the assumption that a linear connection exists between the energy of the primary and that of the window radiation.

Turning to (ii) of fig. 2, representing the constitution of the radiations at V_1 volts, we notice the main differences. The variable primary constituent $c_1c_1'f_1$ is here shown to be more intense and somewhat penetrating, while the aluminium characteristic radiation from the anticathode has considerably increased in ionising value.

We are now in a position to write down in terms of the areas of these curves expressions for the radiation values* of Al and of members of Group B. It is clear from the definition that in the case of a member of Group B, the relative radiation value is equal to s, the constant already introduced. It is shown below that the radiation value of a member of Group A cannot be so simply expressed, but depends on the method of measuring the ionisation.

Expressions are obtained for the radiation value of Al, firstly taking account of the areas of the complete curves to the right of PQ, and, secondly, only taking account of the areas to the right of AB. The first method involves the measurement of "total ionisation," while the second involves the measurement of what may be termed "end ionisation."

1. *Method of "Total Ionisation."*

The relative radiation value ${}_{\mathrm{V}}\mathrm{R}_{\mathrm{T}}$ at V volts of the Al anticathode is given by

$${}_{\mathrm{V}}\mathrm{R}_{\mathrm{T}} = \left(\frac{\text{area } ae + \alpha\,[\text{area } pr + \text{area } cf]}{\text{area } pr + \text{area } cf}\right)100.$$

Not much error will be introduced by neglecting the effect of the window; in which case

$${}_{\mathrm{V}}\mathrm{R}_{\mathrm{T}} = \left(\frac{\text{area } ae + \alpha \text{ area } cf}{\text{area } cf}\right)100 = \left(\alpha + \frac{\text{area } ae}{\text{area } cf}\right)100.$$

Similarly

$${}_{\mathrm{V}_1}\mathrm{R}_{\mathrm{T}} = \left(\frac{\text{area } a_1e_1 + \alpha \text{ area } c_1f_1}{\text{area } c_1f_1}\right)100 = \left(\alpha + \frac{\text{area } a_1e_1}{\text{area } c_1f_1}\right)100.$$

* The relative radiation value of an anticathode A is given by the defining relation

$$\mathrm{R}_{\mathrm{A}} = i_{\mathrm{A}}/i_{\mathrm{S}} \times 100,$$

where R_{A} = the relative radiation value of an anticathode A,
i_{A} = the energy of the Röntgen rays emitted by A,
i_{S} = the energy of the rays emitted under the same experimental conditions, by a standard anticathode S,
100 = the standard radiation value at all generating potentials of the standard anticathode.

2. *Method of "End Ionisation."*

If ${}_{\mathrm{V}}\mathrm{R}_{\mathrm{E}}$ and ${}_{\mathrm{V}_1}\mathrm{R}_{\mathrm{E}}$ are the relative radiation values, using this method at V volts and V_1 volts respectively, then

$$ {}_{\mathrm{V}}\mathrm{R}_{\mathrm{E}} = \left(\frac{\text{area } a'e + \alpha \text{ area } c'f}{\text{area } c'f}\right) 100 = \left(\alpha + \frac{\text{area } a'e}{\text{area } c'f}\right) 100, $$

$$ {}_{\mathrm{V}_1}\mathrm{R}_{\mathrm{E}} = \left(\frac{\text{area } a_1'e_1 + \alpha \text{ area } c_1'f_1}{\text{area } c_1'f_1}\right) 100 = \left(\alpha + \frac{\text{area } a_1'e_1}{\text{area } c_1'f_1}\right) 100. $$

From the diagrams in fig. 2 we see at once from these expressions that

$$ {}_{\mathrm{V}}\mathrm{R}_{\mathrm{T}} < {}_{\mathrm{V}}\mathrm{R}_{\mathrm{E}}, \quad \text{and} \quad {}_{\mathrm{V}_1}\mathrm{R}_{\mathrm{T}} > {}_{\mathrm{V}_1}\mathrm{R}_{\mathrm{E}}, $$

while between V and V_1 there must be some potential V_x where ${}_{\mathrm{V}_x}\mathrm{R}_{\mathrm{T}} = {}_{\mathrm{V}_x}\mathrm{R}_{\mathrm{E}}$.*

We see that, on the views suggested, the relative radiation value of an Al anticathode should depend entirely on the fraction of energy absorbed by the measuring apparatus. That this is experimentally the case is shown in Table I, where it is seen that the potentials corresponding to V and V_1 are 2000 and 3000 volts respectively.

The same theory applies to the case of a Pt anticathode, which emits a strong secondary radiation of much the same penetrating power as that from aluminium.

§ 3. The Dependence of the Energy of Röntgen Radiation—

(A) *On the Nature of the Anticathode.*

(B) *On the Velocity of the Parent Cathode Rays.*

It is well known that all metals do not make equally efficient anticathodes. Kaye,† for example, found that, using cathode rays of rather high velocity, they could be arranged in descending order of efficiency, uranium being at the head of the list and titanium at the foot.

His experiments were carried out in the following general way:—An ionisation chamber was subjected to the action of Röntgen radiation from various anticathodes and the ionisation currents measured. From the value of these ionisations the relative radiation values of the anticathodes (a standard anticathode having been chosen) were calculated from the defining relation already given

$$ \mathrm{R}_{\mathrm{A}} = i_{\mathrm{A}}/i_{\mathrm{S}} \times 100, $$

where

R_{A} = the relative radiation value of an anticathode A,

i_{A} = the ionisation current produced by an anticathode A,

i_{S} = " " " the standard,

100 = the value assigned to the radiation value of the standard.

* In this case f and f_1 would fall on the dotted line of fig. 2.

† G. W. C. Kaye, 'Phil. Trans.,' A, vol. 209, p. 137.

A list drawn up in this way cannot be satisfactorily interpreted unless the absorption coefficients in air of the radiations are known. For an anticathode occupying a high place in the relative radiation scale may owe its position to the emission of very absorbable rays, which will, of course, produce great ionisation in the chamber—which in Kaye's experiments only partially absorbed the rays dealt with. In the present experiments the radiations are totally absorbed, and therefore the results are not open to objections of this nature.

The experimental results of the first part of this section show how the relative radiation values of a number of anticathodes depend on the velocity of the cathode rays incident on them. The experiments were carried out using cathode rays generated at steady potentials ranging from 1600 to 3600 volts, corresponding to velocities between $2 \cdot 4 \times 10^9$ and $3 \cdot 7 \times 10^9$ cm./sec.

The results are shown in fig. 3, and may be verbally stated as follows :—

1. The relative radiation values of the anticathodes Ag, Pb, Sn, Sb, Ni, Cu, Fe, Zn,* are independent of the velocity of the parent cathode rays.

2. The relative radiation values of Al and of Pt rise rapidly as the velocity of the parent cathode rays increases.

Before these relative radiation values can be regarded as quantitatively reliable it will be necessary to be quite certain that the finish of the anticathode surface has no effect. This is a matter requiring experimental investigation. It is quite conceivable that such a surface effect might exist (more especially with slow cathode rays), but even if its existence were proved it would not affect the validity of conclusions based on the *variation* of the radiation values with the generating potential.

The radiation values found under the experimental conditions of this investigation in no way agree with those found by Kaye (*loc. cit.*). These discrepancies are perhaps due to secondary emissions at the high potentials which he used. The graph shows very clearly how it is possible for Al—in spite of its low atomic weight and density—to be the most efficient anticathode between certain limits of cathode ray velocity.

These results were obtained using the particular ionisation chamber arrangement of fig. 4, in which the window of the discharge tube is connected to the case of the chamber and charged to a saturating potential. By this means the total ionisation (see § 2) was measured, since the chamber was long enough to totally absorb the radiation involved.

Now the ionising radiation has had to pass through 0·002 cm. of aluminium window—a thickness which at this stage of the experiments was as small as could be conveniently manipulated. It was thought that interesting results

* Hereafter (and in § 2) referred to as members of Group B.

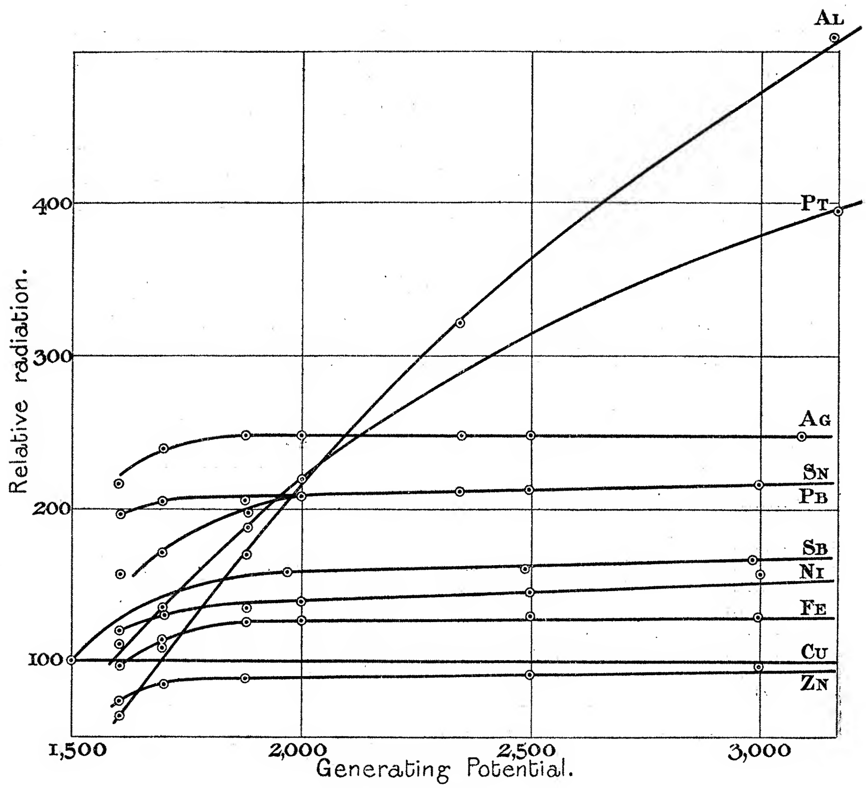
AL
PT
AG
SN
PB
SB
NI
FE
CU
ZN
400
300
200
100
Relative radiation.
1,500
2,000
2,500
3,000
Generating Potential.

Fig. 3.

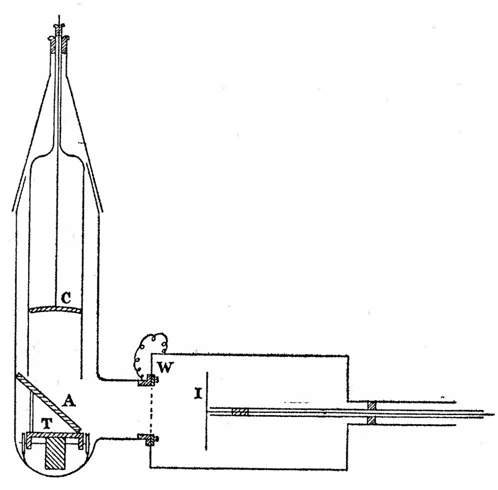
C
W
I
A
T

Fig. 4.

might be obtained by repeating the experiments just described, using a thicker window or an effectively thicker one. In this way, it was thought, light might be thrown on the constitution of the different radiations. This end was attained experimentally by means of the arrangement of fig. 1, in which the gauze front N is a centimetre or so from the window W. The total ionisation is thus not measured, since the ionisation between W and N is not included. We may use the term "end ionisation" to denote what is measured.

The relative radiation values found in this way at generating potentials of 2000 and 3000 volts are given in the following table, which includes, for the sake of comparison, the radiation values from fig. 3* at these two potentials.

Table I.

	2000 volt radiation.		3000 volt radiation.	
	Total ionisation. Fig. 4.	End ionisation. Fig. 1.	Total ionisation. Fig. 4.	End ionisation. Fig. 1.
Cu	100	100	100	100
Pt	**227**	**302**	**400**	**100**
Sn	229	243	236	240
Al	**226**	**298**	**515**	**220**
Ag	262	251	266	281
Fe	132	138	128	122
Cd	112	112	127	136
Ni	152	150	148	144
Zn	93	97		

It will be observed that again Al and Pt, as representative members of Group A, are differentiated from members of Group B, but in this case by *the dependence of their relative radiation values on the amount of energy absorbed by the ionisation chamber.* These results follow from the theory given in § 2 and are easily remembered by its aid.

We have now seen how the *relative* intensity of Röntgen radiation from some anticathodes varies with the velocity of the parent cathode stream. It yet remains to see how this velocity determines the actual energy radiated.

The results for a nickel anticathode are shown in fig. 5, the arrangement of fig. 4 being used. This experiment is but barely alluded to, as I am making it the basis of a separate research. From the graph it will be seen that very little radiation emerges from the window below 1200 volts, at which potential a quite sudden coming-in of ionisation is followed by a linear

* Making use of "total ionisation" by use of fig. 4.

connection between energy of radiation and generating potential (the current passing through the tube being kept constant).

The generating potential, 1200 volts, at which the issuing radiation begins to become appreciable does not depend to any large extent on the thickness

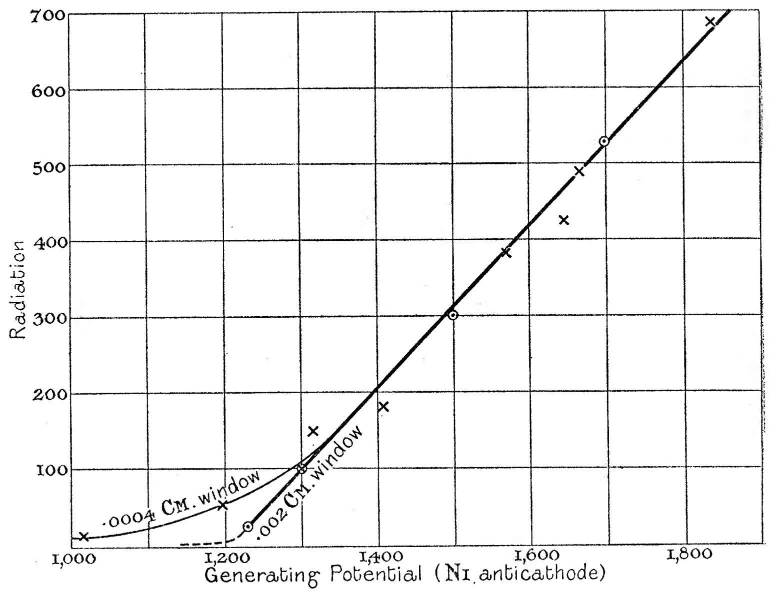

FIG. 5.

of the window. This is shown by the points ⊙ and × on the graph obtained with two different thicknesses of window 0·002 and 0·0004 cm. Preliminary experiments have indicated that the curve of fig. 5, so far as shape is concerned, is the same for all anticathodes as for Ni.

The generating potential 1200 volts, corresponding to a cathode ray velocity of $2{\cdot}1 \times 10^9$ cm./sec., will, on the view put forward in this paper, furnish a value for the minimum cathode ray energy capable of stimulating the Al characteristic radiation.

§ 4. The Dependence of the Absorption Coefficients of the Röntgen Radiation on—

(A) *The Nature of the Anticathode.*

(B) *The Velocity of the Parent Cathode Rays.*

Absorption curves in Cu of the 3000 volt radiation from all the anticathodes are plotted in fig. 6, where the logarithm of the radiation intensity is plotted along the y axis and the thickness of the screen in arbitrary units along the x axis. The ionisation produced after absorption of the

rays in a thickness of copper equal to 5 in fig. 6 is put equal to 100 units. The arrangement of fig. 1 was used, the distance between W and N being about 1 cm., so as to admit the slide carrying the absorbing screens.

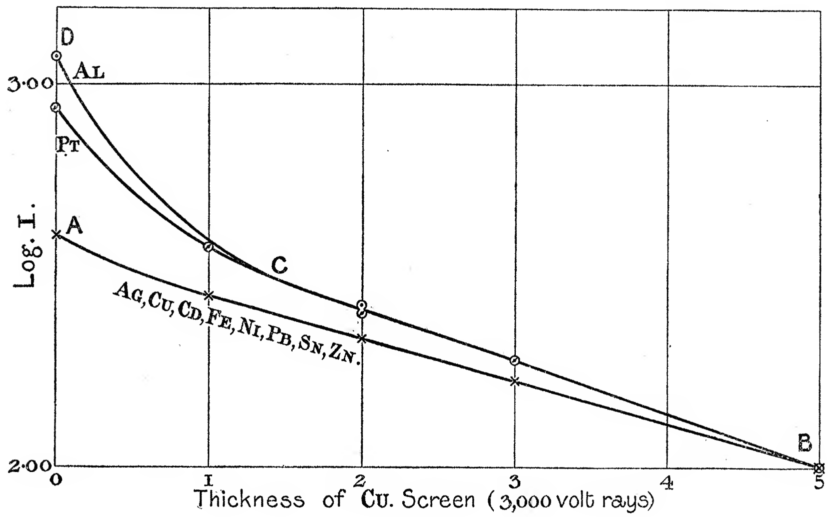

FIG. 6.

It follows from the graph that once again Al and Pt stand apart from the remaining anticathodes. In this experiment their absorption curves have an early steep part, whereas the similar curves for members of Group B are coincident straight lines with just a very slight initial steepening.

These experimental results can receive only one interpretation, and that is that the 3000 volt radiation from members of the B group of anticathodes is very nearly homogeneous and independent of the nature of the anticathode,* whereas that from Al and Pt contains not only a radiation of the same penetrating power as that from Group B, but also one of a considerably softer character.

I have plotted absorption curves similar to those of fig. 6 at different generating potentials, and it seems that (using an Al anticathode) the part CB of the absorption curve DCB becomes steeper as the generating potential diminishes. At 2600 volts, or thereabouts, CB disappears, and the complex curve DCB degenerates to practically a straight line,† corresponding to the earlier steep part DC. At potentials less than 2600 volts the slope of DC remains much the same, although the intensity of the radiation itself is

* J. J. Thomson, "On the Electrical Origin of the Radiation from Hot Bodies," 'Phil. Mag.,' Aug., 1907, p. 230. This paper anticipates theoretically this experimental result.

† The radiation is not quite homogeneous.

continually diminishing. When an anticathode of Group B is used instead of Al, much the same sequence occurs, only in this case the energy escaping from the tube is much less.

The variation in absorption coefficient λ/ρ with the generating potentials in volts is shown in fig. 7.

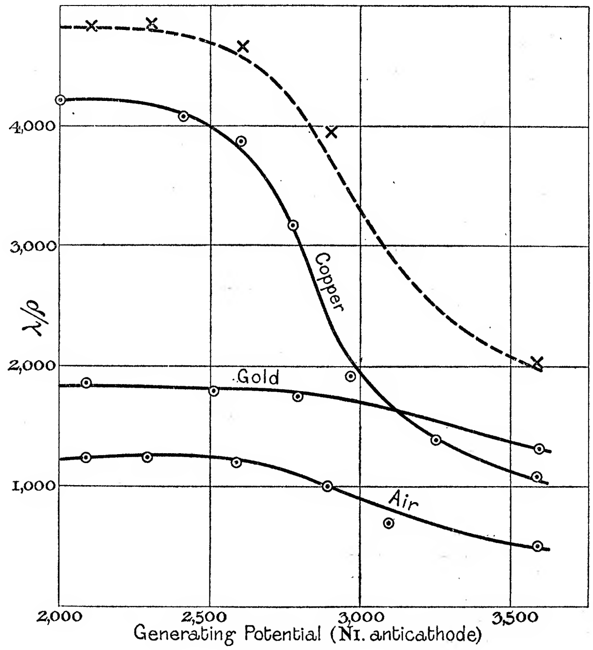

FIG. 7.

In these experiments a Ni anticathode, as representative of Group B, was used. The absorption coefficients plotted in fig. 7 correspond to the early part of the curves of fig. 6, taken of course at different potentials. The graphs show how the slight initial steepening observable at 3000 volts becomes very important at lower generating potentials, when, on the theory of § 2, the variable primary constituent of the examined radiation is becoming of less importance. These absorption coefficient variations have been observed for screens of gold, copper, tin, air,* and aluminium. With the exception of the latter the general results are independent of the material of the screen.

From fig. 7 it is clear that, taking the air curve as typical, the absorption coefficient of the radiation issuing from the tube is up to 2600 volts independent of the generating potential.† At generating potentials above

* The dotted curve of fig. 7 is the air curve with its ordinates quadrupled.

† This remarkable result has already been obtained with Al screens for a similar range of generating potentials by W. Seitz, 'Phys. Zeitschr.,' 6 Jahr., No. 23, p. 757.

2600 volts the graph shows a sudden diminution in λ/ρ, and the value of V at which this drop takes place is independent of the screen. The potential at which this diminution in λ/ρ appears must depend on the thickness of window used, because drawing the ionisation chamber further away from the window has the effect of shifting the bend in the curve towards a higher value of V.

It will be clear that up to 2600 volts or thereabouts the radiation emerging from the window or, rather, entering an ionisation chamber a centimetre away, is mainly (to within a few per cent.) the aluminium characteristic radiation. The absorption coefficients of this radiation (using the 2700 volt radiation from Al) in various absorbing screens are shown in the following table. The very high values for Cu and Ag screens are noteworthy.

The last column shows the parallel coefficients for the softest characteristic radiation studied by Barkla, namely, that from chromium:—

Table II.

Screen.	λ/ρ.	λ/ρ (Cr radiation).*
Pt	2010	516·8
Au	1760	507
Cu	3900	143
Ag	2020	580·5
Sn	1030	713·7
Al	580	136
Air	1150	—

* Barkla and Sadler, 'Phil. Mag.,' 1909, vol. 17, p. 749.

It has been mentioned that the curves of fig. 7 are of the same general shape for the screens Au, Cu, Sn, and air, but this does not quite hold in the case of Al screens. The horizontal part of the curve persists for a rather greater distance, and shows in fact a very slight tendency to rise before finally falling towards the V axis.

§ 5. The Corpuscular Radiation excited by the Impact of Soft Röntgen Rays on Metallic Surfaces.

For the purposes of the experiments described in this section the ionisation chamber was cemented on to the discharge tube in the manner shown in fig. 4. By means of liquid air and a charcoal tube the chamber could be evacuated.

The Röntgen rays from the aluminium anticathode passed through the window W and fell on the plate I. When the plate I was Cu, Pb, Ni, Ag,

or Zn the same effects were always observed, viz., that that plate received a negative charge. This was proved to be due to the emission of negative particles from the window by applying a strong magnetic field across it. When the magnet was "on" no deflection could be observed in the electroscope in two minutes. When the magnet was "off" the rate of negative charging up of the electroscope was about two divisions a minute, the current through the discharge tube being 1/5 milliampère at 3400 volts.

When the plate A was either aluminium or platinum, the incidence of the rays caused the electroscope to charge up positively, the rate being increased considerably when the magnetic field was switched on. The conclusion is, therefore, that the emission by aluminium and platinum of a strong secondary Röntgen radiation is accompanied by an emission of corpuscles.

§ 6. Summary and Conclusions.

1. The variations with the generating potential (which is proportional to the $(\text{velocity})^2$ of the primary cathode rays) of the relative radiation values of 10 anticathodes have been studied. The potential limits were 1500 to 3600 volts. Eight of these anticathodes (members of Group B) were found to have definite radiation values not depending on the generating potential, while the remaining two (Al and Pt) rapidly increased their radiation values with rising potentials.

At any definite generating potential the actual radiation values of Al and Pt depend enormously on the amount of energy absorbed by the ionisation chamber, whereas the radiation values attached to the members of Group B are not so influenced.

If a particular view of the constitutions of the radiations be taken (see § 2) these results are easily explained, and, moreover, fall into line with other results of an entirely different kind. Briefly this view is as follows :—

The behaviour of the 10 anticathodes studied under the particular experimental conditions of this research leads to their classification under two headings, termed for convenience Groups A and B. At a definite generating potential the radiations from members of Group B are regarded as differing amongst themselves only in quantity (ionising power) (fig. 3) and not in quality (absorption coefficient) (fig. 6). The quality, however, does depend on the generating potential (fig. 7).

The radiations from anticathodes of Group A (Al and Pt) also are regarded as containing a component whose quality depends on the generating potential. But they are also imagined to contain relatively strong constituents of the characteristic type, which are peculiar in their possible possession of absorption coefficients less than those of the exciting primary rays. In other words

it is supposed that these characteristic radiations can be stimulated by less penetrating exciting rays.

Such an hypothesis is not glaringly absurd, since the law to which it does not conform is after all only a restatement of Stokes's law of light fluorescence, and Prof. R. W. Wood has shown its limited applicability.

2. Below a generating potential of 1200 volts only a very weak Röntgen radiation can be detected. This is regarded as a secondary effect of the window. The sudden coming in of relatively strong radiation at 1200 volts is very striking (fig. 5). Above 1200 volts there is a linear connection between the energy of the Röntgen rays emerging from the tube and the energy absorbed by the discharge, the current through the tube being kept constant.

3. Over a certain range of generating potentials the speeding-up of the parent cathode rays produces no effect on the absorbability of the emerging radiation (fig. 7). This also is regarded as an effect due to secondary radiation from the window.

In fact with the measuring chamber 1 cm. from the Al window the view held is that the only radiation which is measured below 2600 volts is, with any anticathode, the aluminium characteristic radiation.

At 3000 volts the radiations from Al and Pt and members of Group B have been analysed, and the results show conclusively the emission of secondary radiation from the former two, and its almost complete absence in the rays emitted by the latter eight.

4. It has been shown that Al and Pt under the impact of these soft rays emit corpuscular radiation in addition to the above-mentioned secondary Röntgen radiation. In this respect again Al and Pt are differentiated from members of Group B, which do not emit under similar circumstances any measurable quantity of charged particles.

It gives me pleasure to thank Prof. Sir J. J. Thomson for his interest in this investigation, which was carried out at the Cavendish Laboratory.